Design a Nonlinear Adaptive Controller for Power System Stabilizer

Mehran Rashidi, Farzan Rashidi, Hamid Monavar

***Abstract*—This paper proposes the design of power system stabilizer based on fuzzy logic and the sliding mode controller. The control objective is to enhance the stability and to improve the dynamic response of a single-machine power system operating in different conditions. Simulation results show that this control strategy is very robust, flexible and alternative performance. First a sliding-mode controller with an integral operating switching surface is designed. Then a fuzzy sliding mode controller is investigated in which a simple fuzzy inference mechanism is used to estimate the upper bound of uncertainties, then chattering is reduced. A detailed sensitivity analysis for a one-machine-infinite-bus system reveals that the fuzzy sliding-mode power system stabilizer is quite robust to wide variations in operating load and system parameters.**

***Index Terms*—power system stabilizer, Fuzzy sliding-mode control, Single-machine**

I. INTRODUCTION

Power system stability problem has received a great deal of attention over the years. Over a last four decades, a large number of research papers have appeared in the area of PSS [1]. Research has been directed towards obtaining such a PSS that can provide an optimal performance for a wide range of machine and system parameters.

The action of a PSS is to extend the angular stability limits of a power system by providing supplemental damping to the oscillation of synchronous machine rotors through the generator excitation [2]. This damping is provided by an electric torque applied to the rotor that is in phase with the speed variation. Once the oscillations are damped, the thermal limit of the tie-lines in the system may then be approached. This supplementary control is very beneficial during line outages and large power transfers [3]. However, power system instabilities can arise in certain circumstances due to negative damping effects of the PSS on the rotor. The reason for this is that PSSs are tuned around a steady-state operating point; their damping effect is only valid for small excursions around this operating point. During severe disturbances, a PSS may actually cause the generator under its control to lose synchronism in an attempt to control its excitation field [3].

A typical configuration of a single-machine infinite-bus power system is shown in Fig1. The generator is equipped with an automatic voltage regulator (AVR) to control its terminal voltage and improve its dynamic stability limits. However, the AVR may add negative damping to the system and worsen its relative stability [4,5]. Some conventional power system stabilizers (PSS) are proposed in [4,5] to improve stability by adding a phase lead to the system.

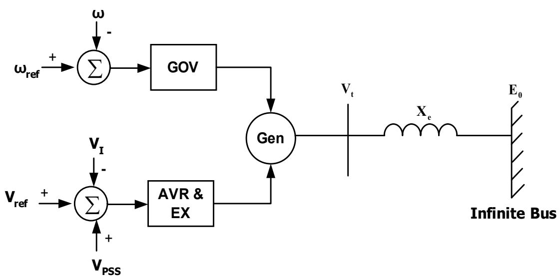

Fig 1 . Basic components of a single-machine infinite-bus power system

Since power systems are highly nonlinear, conventional fixed-parameter PSSs cannot cope with great changes in operating conditions. There are two main approaches to stabilizing a power system over a wide range of operating conditions, namely adaptive control [6-8] and robust control [9-11]. Adaptive control is based on the idea of continuously updating the controller parameters according to recent measurements. However, adaptive controllers have generally poor performance during the learning phase, unless they are properly initialized. Successful operating of adaptive controllers requires the measurements to satisfy strict persistent excitation conditions, otherwise the adjustment of the controller's parameters fails. Robust control provides an effective approach to dealing with uncertainties introduced by variations of operating conditions. Among many techniques available in the control literature H_∞ and variable structure control have received considerable attention as PSSs. The H_∞ approach is applied to the design of the PSS for a single machine infinite-bus system [9]. The basic idea is to carry out a search over all possible operating points to obtain a frequency bound on the system transfer function. Then a controller is designed so that the worst-case frequency response of the lased loop system lies within prespecified frequency bounds. It is

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noted that the H_∞ design requires an exhaustive search and results in a high order controller. On the other hand the variable structure control is designed to drive the system to a sliding surface on which the error decays to zero [10-12]. Perfect performance is achieved even if parameter uncertainties are presented. However, such performance is obtained at the cost of high control activities (chattering). In this study a fuzzy sliding-mode control system which combines the merits of the sliding-mode control and the fuzzy inference mechanism is proposed. In the sliding-mode controller a switching surface that includes an integral operating [12] is designed, when the sliding mode occurs the system dynamic behaves as a robust state feedback control system. Furthermore, in the general sliding-mode control the upper bound of uncertainties, which include parameter variations and external load disturbance, must be available. However the bound of uncertainties is difficult to obtain in advance in practical applications. A fuzzy sliding-mode controller is investigated to resolve this difficulty in which a simple fuzzy inference mechanism is used to estimate the upper bound of uncertainties. Simulation results for a one-machine-infinite-bus system are presented to show the effectiveness of the proposed control strategies in damping oscillation modes.

II. MACHINE-INFINITE BUS SYSTEM MODEL

The small perturbation transfer function block diagram of the machine-infinite bus system relating the pertinent variables of electrical torque, speed, angle, terminal voltage and flux linkages is shown in Fig.2.

The initial *d-q* axis current and voltage components and torque angle needed for evaluating the K constants are obtained from the steady-state equations, and the system data are as follows[5]:

$V_{do} = 0.8211 p.u$, $I_{do} = 0.8496 p.u.$, $E_{qo} = 0.8427 p.u$

$V_{qo} = 0.5708 p.u.$, $I_{qo} = 0.5297 p.u.$, $V_o = 1.0585 p.u.$

$\delta_o = 77.4^0$

The K constants:

$k_1 = 1.15839$ $k_2 = 1.43471$ $k_3 = 0.36$

$k_4 = 1.83643$ $k_5 = -0.11133$ $k_6 = 0.31711$

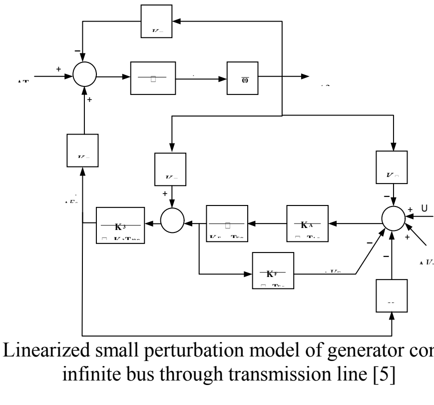

Fig. 2. Linearized small perturbation model of generator connected to infinite bus through transmission line [5]

The dynamic model of the system is obtained from the transfer function model (Fig.2) in state-space from as [5]:

$$\dot{x}(t) = Ax(t) + bu(t) \quad (1)$$

Where $x = [\Delta w \ \Delta\delta \ \Delta E_q^{'} \ \Delta E_\mu \ \Delta V_R \ \Delta V_E]^T$ and it is the stabilizing signal obtained through PSS. The value of A and b are given in appendix.

III. SLIDING MODE AND FUZZY SLIDING MODE CONTROLLERS

Fuzzy logic control (FLC) is a method utilizing those fuzzy experiential and/or experimental rules to decide control actions [13]. In past years, FLC has found many successful applications in industrial. However, traditional fuzzy controller lacks formal synthesis techniques and all the decision rules are experience oriented. In other words, the FLC is human dependent.

Sliding Mode Controller (SMC) is a particular type of variable structure control systems that is designed to drive and then constrain the system to lie within a neighborhood of the switching function. There are two main advantages of this approach. Firstly, the dynamic behavior of the system may be tailored by the particular choice of switching functions. Secondly, the closed-loop response becomes totally insensitive to a particular class of uncertainty and external disturbances [14]. In addition, the ability to specify performance directly makes sliding mode control attractive from the design perspective. This design approach consists of two components. The first, involves the design of a switching function so that the sliding motion satisfies design specifications. The second is conserved with the selection of a control law, which will make the switching function attractive to the system state. In general sliding-mode control the upper bound of uncertainties, which include parameter variations and external load disturbance, must be available. However, the bound of uncertainties is difficult to obtain in advance for practical applications.

The fuzzy sliding mode control (FSMC) technique, which is an integration of variable structure control and FLC, provides a simple way to design FLC systematically. The main advantage of FSMC is that the control method achieves asymptotic stability of the system. Another attractive feature is that the method can minimize the set of FLC and provide robustness against model uncertainties and external disturbances. In addition, the method is capable of handling the chattering problem that is arisen in the traditional sliding mode control.

Therefore a fuzzy sliding-mode controller is proposed in which a fuzzy inference mechanism is used to estimate the upper bound of the lumped uncertainty. The fuzzy inference mechanism can construct the estimation model of the lumped uncertainty. The fuzzy inference mechanism uses prior expert knowledge to accomplish control object more efficiently. Consider equation (1) with uncertainties

$$\dot{x}(t) = (A + \Delta A)x(t) + (b + \Delta b)u(t) \quad (2)$$

Where ΔA and Δb are denoted as the uncertainties introduced by system parameters. Reformulate equation (2), then

$$\dot{x}(t) = Ax(t) + b(u(t) + E(t) \quad (3)$$

Where *E(t)* is called the lumped uncertainly. Here the switching surface with integral operation for the sliding-mode PSS is designed as follows [12]:

$$S(t) = C[x(t) - \int (A + bk)x(r)dr] = 0 \quad (4)$$

where *C* is set as a positive constant matrix and *K* is a state-feedback gain matrix. From equation (4), if the state trajectory of system equation (3) is trapped on the switching surface equation (4), namely $S(t) = \dot{S}(t) = 0$, the equation dynamic of system equation (3) is governed by the following equation:

$$\dot{x}(t) = (A + bk)x(t) \quad (5)$$

It is obvious, seen from equation (5) that *x(t)* will converge to zero exponentially if the poles of system equation (5) are strategically located on the left-hand plane. Thus, the overshoot phenomenon will not occur, and the system dynamic will behave as a state feedback control system. From equation 3, 4 and 5, in the sliding-mode S(t)=0 the controlled system equation 3 is insensitive to the uncertainties $\Delta Ax(t)$ and $\Delta bu(t)$. Also the closed-loop eigenvalue, $(A + bk)$ in the sliding mode can be arbitrary assigned by *K*. Based on the developed switching surface a switching control law that satisfies the hitting condition and guarantees the existence of the sliding mode is designed. A sliding-mode PSS (SMPSS) is proposed in the following:

$$U(t) = Kx(t) - f\,\mathrm{sgn}(S(t)) \quad (6)$$

where $\mathrm{sgn}(.)$ is a sign function defined as

$$\mathrm{sgn}(S(t)) = \begin{Bmatrix} +1 & \text{if} & \mathrm{S(t)} > 0 \\ -1 & \text{if} & \mathrm{S(t)} < 0 \end{Bmatrix} \quad (7)$$

and f is defined as $|E(t)| \le f$ since Cb and f are positive, according to the SMPSS obtained by equation (7), it can shown that:

$$S(t)\dot{S}(t) = S(t)[C\dot{x}(t) - C(A + bk)x(t)\} < 0 \quad (8)$$

It is obvious that the SMPSS obtained by equation (6) guarantees the existence condition of the sliding mode as follow:

$$\lim_{x \to 0} S\dot{S} < 0 \quad (9)$$

and stabilizes the system equation (3). When the state $x(t)$ is trapped on the switching surface, the dynamic of the system is governed by equation (5), which is always stable, the state $x(t)$ will slide into the origin.

With replacing f by k_f in (6), the following equation can be obtained:

$$U(t) = KX(t) - K_f\,\mathrm{sgn}(S(t)) \quad (10)$$

Where k_f is estimated by fuzzy inference mechanism. The membership function for the fuzzy sets corresponding to switching surface S and $\dot{S}$ are defined in Fig.3. Since only three fuzzy subsets, N, Z and P are defined for S and $\dot{S}$ the fuzzy inference Mechanism only contains nine rules.

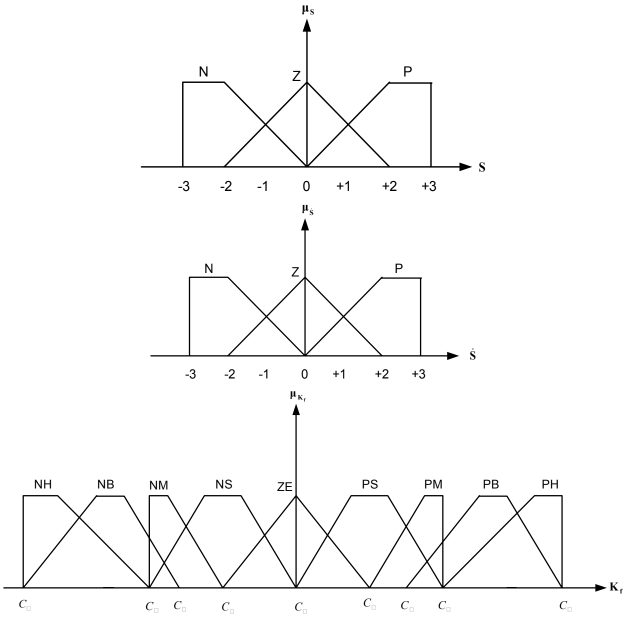

Fig.3 Membership functions of fuzzy sets

The *i*th rule for a Sliding Mode Fuzzy Controller is expressed as follows:

R^i: *if S is* A_i *and* $\dot{S}$ *is* B_i *then* K_f *is* C_i

where A_i, B_i and C_i are labels of fuzzy sets representing the linguistic values of, *S,* $\dot{S}$ and K_f respectively, which are characterised by their membership functions.

Fuzzy output K_f can be calculated by the weighted average defuzzification as follow:

$$K_f = \frac{\sum_i w_i C_i}{\sum_i w_i} \quad (11)$$

Where C_i is the membership function of the *ith* rule and w_i is the degree of validity of the *ith* rule.

IV. SIMULATION RESULTS

The state feedback gain *K* is designed to be [-681 11.2 32.7 0.161 0.452 2.95] for closed-loop poles assignment at [-8.6 -9.1 -9.7 -10.2 -10.6 -10]. f is selected to be 0.15 p.u. Fig.4a and 4b, show the dynamic responses for Δw and $\Delta\delta$ considering SMPSS and FSMPSS following a 1.5% step increase in ΔT_m. A detailed sensitivity analysis is carried out to understand the sensitivity of the system with SMPSS and FSMPSS to changes in significant system parameters such as line reactance x_e, inertia constant H, field open-circuit time constant T'_{do}, AVR gain K_A and loading conditions P and Q over a wide range, from their nominal values. The dynamic responses for Δw and $\Delta\delta$ following a 1.5% step increase in ΔT_m were obtained and analyzed. Fig.5a and 5b show the dynamic responses of the system with SMPSS and FSMPSS. It can be clearly seen that dynamic performances of the system with SMPSS and FSMPSS are quite insensitive to $\mp 25\%$ variations in line reactance x_e from its nominal value. Further, sensitivity analysis considering $\mp 25\%$ change in P, Q, K_A, H and T'_{do} from their nominal values revealed that the SMPSS and FSMPSS are quite robust to wide variations in these parameters.

V. CONCLUSION

This paper proposes the design of power system stabilizer based on fuzzy logic and the sliding mode controller. The control objective is to enhance the stability and to improve the dynamic response of a single-machine power system operating in different conditions. Simulation results show that this control strategy is very robust, flexible and alternative performance.

VI. REFERENCES

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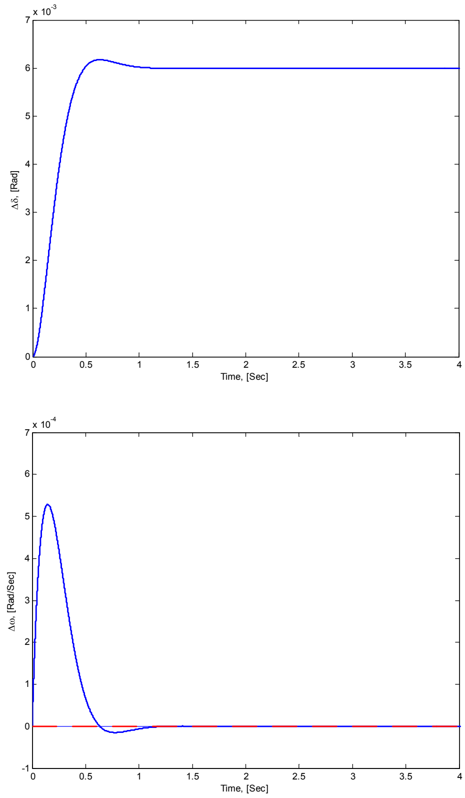

Fig.4a: Dynamic responses for $\Delta\delta$ and Δw with FSMPSS

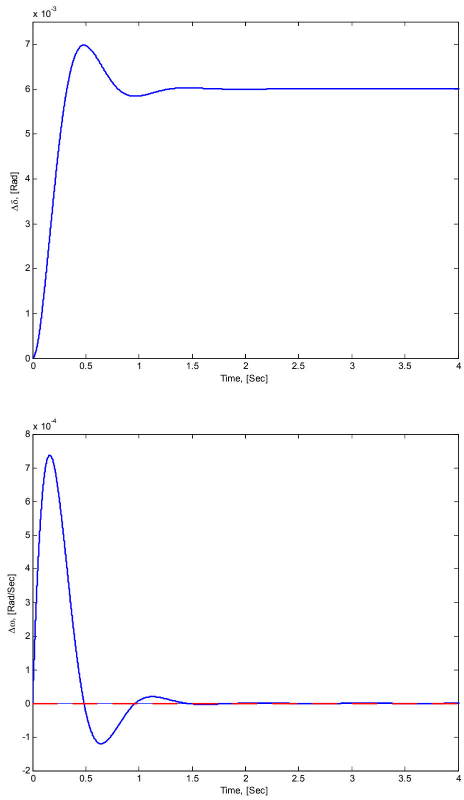

Fig.4b: Dynamic responses for $\Delta\delta$ and Δw with SMPSS

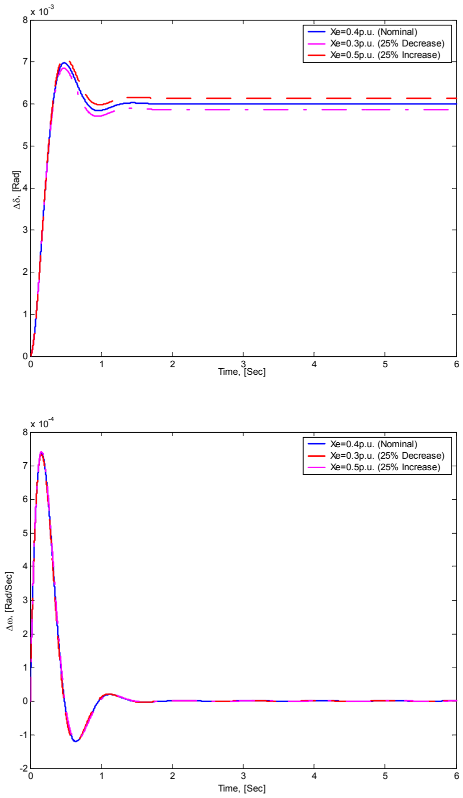

Fig.5a. Dynamic responses for ∓ 25% change in line reactance with SMPSS

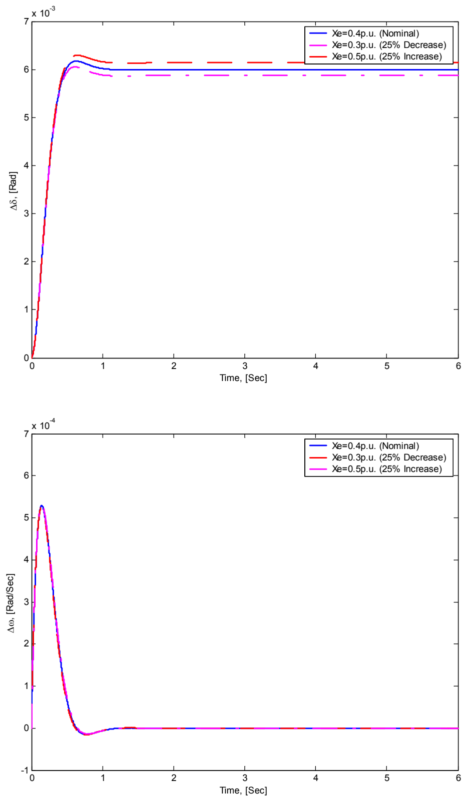

Fig.5b. Dynamic responses for ∓ 25% change in line reactance with FSMPSS

VII. APPENDIX

The nominal parameters of the system and the operating conditions used for the sample problem investigated are given below. All data are given in per unit of value, except that H and time constants are in seconds.

A. Generator

$H = 5\,\text{s} \quad T'_{do} = 6\ \text{s} \quad x_d = 1.6 \quad x'_d = 0.32 \quad x_q = 1.55$

B. IEEE type-1 excitation system

$K_A = 50$, $T_A = 0.05$ s, $K_E = -0.05$, $T_E = 0.5$ s, $K_F = 0.05$, $T_F = 0.5$ s

C. Transmission line

$x_e = 0.4$, $r_e = 0$

D. Operating Conditions

$P = 1$, $Q = 0.05$, $V_{to} = 1$, $f = 50$ Hz

The linear state-space model of the system is given by

$\dot{x} = Ax + bu$

where $x = [\Delta w\ \ \Delta\delta\ \ \Delta E_q\ \ \Delta E_\mu\ \ \Delta V_R\ \ \Delta V_t]^T$

$$A = \begin{bmatrix} 0 & -\frac{K_1}{2H} & -\frac{K_1}{2H} & 0 & 0 & 0 \\ 2\pi f & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{K_4}{T_{do}} & -\frac{1}{K_3 T'_{d0}} & \frac{1}{T'_{d0}} & 0 & 0 \\ 0 & 0 & 0 & -\frac{K_5}{T_r} & \frac{1}{T_r} & 0 \\ 0 & -\frac{K_3 K_A}{T_A} & -\frac{K_5 K_A}{T_A} & 0 & -\frac{1}{T_A} & -\frac{K_A}{T_A} \\ 0 & 0 & 0 & -\frac{K_F K_A}{T_E T_r} & \frac{K_F}{T_A T_F} & -\frac{1}{T_F} \end{bmatrix}$$

$$b = [0\ \ 0\ \ 0\ \ 0\ \ k_A / T_A\ \ \ 0]^T$$